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ABSTRACT

Challenged by the patterns of inquiry and learning inherent in the new elementary science curricula, a new program was developed to prepare future elementary teachers to handle the new materials with some degree of security and competence. The University of Washington Physics Department has developed a new course in physical science, conducted in an individualized self-paced manner, with laboratory investigation, observation, and manipulation preceding all discussion and motivating the formation of concepts and models. The course begins with selected portions of College Introductory Physical Science (CIPS) and continues with selected portions of The Project Physics Course. The course runs for three quarters, and students must take two quarters to receive credit with the third quarter optional. No formal lectures are presented; rather, small group discussions are held with students who are at a common place in the course. Students take oral or written examinations as they finish sections of the course and then proceed to the next section. (YS)

Anatomy of a Physical Science Course for Future Elementary Teachers and Non-Science Majors*

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Challenged by the patterns of inquiry and learning inherent in the new elementary science curricula, many colleges and universities are striving to develop programs that will prepare future elementary teachers to handle the new materials with some degree of security and competence. In the University of Washington Physics Department, our response has taken the form of a new course in physical science, conducted in an individualized, self-paced manner, with laboratory investigation, observation, and manipulation preceding all discussion and motivating the formation of concepts and models.

Rather than dilute our efforts with the development of still another set of curricular materials to add to the already massive accumulation, we have elected to make use of existing materials, modifying specific units, enhancing or expanding various contexts and perspectives as the need is defined through close observation of student successes, difficulties, and learning experiences. Such observation has provided the basis for selection of subject matter, defining educational objectives, and determining the volume of material to be covered. Descriptions of the content, framework, and mode of operation of the course are intertwined in the following story.

The course begins with selected portions of College Introductory Physical Science (CIPS) [1] and continues with selected portions of The Project Physics Course [2], both programs lending themselves to a laboratory oriented, self-paced mode of instruction, laboratory work being integral to the text. From the CIPS materials we take the genesis of the atomic-molecular model: why do we believe in the discreteness of the structure of matter on the microscopic scale? As we then go on into the description of motion, the model of the solar universe, the unification of terrestrial and celestial phenomena in the Newtonian Synthesis, we keep building and extending the kinetic theory model at the same time. Thus we keep showing how science, as it developed deeper insights into the order exhibited in macroscopic phenomena, transferred these insights to generating a view of the microscopic world that transcends our senses.

The course runs for a full year, and students must take two quarters to receive credit; the third quarter is optional, but about 60% of the students have elected the option. About 60% of the students enrolled are future teachers, and 40% come solely for general education purposes. In successive years, the enrollemnt has grown from 13 to 30 to 55.

Students come to class for 3 one-hour and 1 two-hour sessions each week *. They receive a "unit outline" which guides

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*When course enrollment exceeds the capacity of our laboratory for the scheduled blocks of hours (about 80) as it promises to do in the near future, we will shift into an "open lab" framework in which students can come to the laboratory during any of a reasonably wide range of hours in which staff will be on duty.

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their study for a period of one or two weeks and proceed to work in pairs at their own pace. The unit outline indicates a body of experimental investigations and text material, problems to be solved, questions to be answered. Finally there is a specific description of what the student should be able to do and deal with when he has completed the unit (Explain clearly in your own words the function of the metal clip or 'rider' that slides along the arm of your balance. Define the concept of 'density' operationally. Make up arithmentical problems of your own, for example, a problem in predicting the total volume that would be occupied by a given mass of material of known density; select reasonable numerical values for the known quantities; explain in your own words the arithmetical reasoning behind your solution.)

When they feel they have completed a unit to their satisfaction, students answer a few written questions or have an oral interview with a staff member to check their grasp of the material before going on to the next unit. A reasonable, first level grasp of the ideas and lines of reasoning is considered adequate at this point, and students are rarely sent back for additional work in the same unit. Deeper solidification of the student's understanding, which is almost invariably needed, is cultivated not by insistent hammering of the initial encounter but by continual spiralling back to earlier ideas, invoking these ideas in repeatedly extended contexts, and using them in new juxtapositions.

On the first day of class, students start working with the equal-arm balance which is to be used in the investigations pursued in the CIPS text, and an early task involves calibrating a scale for the rider on the balance arm. As students calibrate the scale, staff members start asking questions that are not raised in the text: In moving the rider around on the arm, you are not changing the amount of matter on that side of the balance as you do when you add or remove weights from the pan; you are simply moving around an object of unchanging weight. How can this have anything to do with the operation of "weighing" ? In the scale being marked off along the track of the rider, you seem to have marked off uniform intervals. What is the justification for uniform intervals? How do you know that the scale spacing should not be non-uniform ?

As the students become puzzled by these questions, it is suggested that a more general, empirical study of balancing (see-saws in the form of meter sticks suspended at their centers are readily available around the lab as are weights to hang in different positions on either side) might help provide the justifications being asked for. Students thus digress to carry out an investigation beyond the guidance of the text; they encounter the arithmetical concepts and reasoning intrinsic to this problem, and return to apply the broader concepts to a justification of what they are doing with the rider and its scale on the balance arm. At the same time they have carried out an investigation dealt with in many of the elementary science curricula.

This sequence illustrates, at the very start, certain key aspects of our approach, aspects that occur repeatedly in virtually all subsequent developments: broadening a particular context beyond the demands of the text (operation of the balance) to give it a wider range and meaning (connection to the arithmetic of balancing in general and the concept of a "turning effect"); cutting across subject matter content in the new elementary science materials; continually raising questions as to "what is the justification for...?" "how do know that....?" "why do we believe....?" about everything we do.

Laboratory work, problem solving, conversation among students and between students and staff go on in every class session, with all meetings being held in a laboratory rather than a classroom. There is no formal lecturing, but, when a group of students is ready at a particular point, they are drawn together for a discussion which strives to organize ideas and open perspectives that the students are not likely to see without help and guidance from a teacher.

For example, immediately after students have measured the densities of a variety of objects (metals, stones, liquids, etc.) and begin to understand density as an intrinsic property of different materials, a discussion group is formed. The group is given the numerical values for the total mass and radius of the Earth (later in the course they will have the opportunity to see where these numbers come from; the assertion of the numbers at this early stage of the game fosters some curiosity about them) and are led to calculate the density of the Earth by dividing overall mass by overall volume. The value comes out to be about 5.5 grams/cm^3 whereas the data assembled in class for stones lie between 2.8 and 3.0. What does the discrepancy between 5.5 and 2.9 mean ? What might it be telling us about the Earth? What more detailed questions about the Earth are suggested?

The discussion is invariably lively: Material within the Earth is being squeezed by the load above it. Do materials get more dense when squeezed? Could there be different material substances, more dense than stone, in the interior of the Earth? What is the meaning of the single number obtained when mass is divided by volume in the case of a non-homogeneous object? Is this an "average"? How does the concept of "average" apply here?

As far as the interior of the Earth is concerned, it is obvious that more questions are asked than answered at this stage of the game; but students begin to see the power behind a simple comparison of numbers obtained in different ways; they have used the concept of density in a non-trivial way and have made a significant inquiry about the Earth as a whole. They see how one factual insight precipitates a whole line of questioning that would not otherwise arise; they discern the point at which questions cannot be pursued further without additional factual information from other sources.

Later, when the students perform an electrolysis experiment, the staff is primed to go around asking how much liquid water might have been used up in forming the 20 or so cm^3 of gas they have collected. Few have any sense at all of the order of magnitude; many respond that the volume of liquid water electrolyzed must have been about equal to the volume of gas collected. A few leading questions can now send them back to more pencil and paper work with volumes, densities, and conservation of mass; the inquiry has become motivated by a challenge and a question related to direct experience. When, through their own calculations, they realize how tiny an amount of liquid has been electrolyzed, they begin to appreciate the real meaning of the factor of 1000 between the densities of gases and liquids. Subsequently in building up the kinetic molecular model, they are fully ready to introduce the assumption that the molecules of gases are vastly farther apart, on the average, than the molecules of liquids, and they see this as a plausible step in construction of a theory, not as just an item in a list of unmotivated, ad hoc assumptions that must be memorized because the list might be called for on a test.

Still later in the course, after development of the concept of force, we spiral back to density again, this time in the context of understanding the floating or sinking of objects in a liquid. By now the concept is firmly established, and at the same time we cut across another item of subject matter common to the elementary science curricula. (As another illustration of expanding a given context and making contact with elementary science materials: the CIPS electrolysis experiment referred to above is followed by a digression into an investigation of current electricity essentially along the lines of the Elementary Science Study unit on Batteries and Bulbs. This provides a change of pace from the sequence of chemical experiments and is also a fine exercise in experimenting, observing, and model building.)

From the very beginning of this program, we have been keenly aware, on a subjective basis, of the problem more recently given quantitative documentation by McKinnon and Renner[3]:

"[A major fraction of the students we are addressing are unable to] think logically about volume conservation, reciprocal implication of two factors, the elimination of a contradiction, the separation of several variables, and the exclusion of irrelevant variables from among those relevant to problem solutions." Furthermore, our own experience shows that a still larger fraction has had no practice in the most basic arithmetical reasoning: they do not understand the meaning of the words "ratio" and "per"; they do not comprehend division as anything but a memorized algorithm; they do not associate "so much of the numerator with one chunk of the denominator" after the division has been performed; they are completely unable to solve "word problems" analagous to those that children should be able to do in 4th, 5th, or 6th grade arithmetic.

We devote major effort and substantial amounts of time to an attack on these problems of intellectual development. At the point that the law of conservation of mass emerges in the CIPS work, we underline its power, uniqueness, and significance by having a discussion of the general idea of conservation: What makes a conservation statement so powerful? Let us make up additional illustrations of its predictive power. Can we give examples of situations in which a property is not conserved? What happens to volume if we pour a liquid into containers of different shape? What happens to volume in cases of evaporation, chemical change, the electrolysis experiment? What happens to total surface area when we fragment a solid? What might this have to do with the rate at which a solid dissolves?

In a similar way, we pay careful attention to the logic behind all the experiments students perform. The staff is primed to raise questions about every aspect of apparatus set-up and experimental plan as well as the line of reasoning in interpreting results. All the questioning that is being referred to is always socratic; the students are led to answers, not told.

Even more effort is invested in clearing up the difficulties with arithmetical reasoning. Almost all the students coming to this course have initial difficulty in interpreting density as the number of grams associated with each individual cubic centimeter. They then have still greater difficulty articulating the line of reasoning that, if we have 300 grams of stone with density 2.9, the volume of the stone is to be found by dividing 300 by 2.9 because we seek to know how many packages of 2.9 grams each are present in 300, each package corresponding to one cubic centimeter. They desperately seek to avoid this reasoning and explanation by manipulating a formula in a memorized, but never understood, procedure.

Many students have to be carried back to consideration of a grocery box costing 75¢ and weighing 14 ounces: What is the interpretation, in words, of the number 75/14 ? What is the interpretation of the number 14/75 ? (The latter causes enormous difficulty to many students.) Then one can spiral back to the arithmetic of density. With an appreciable number of students, this sequence must be repeated several times. In many instances, it is important to ask them to subtract 14 successively from 75 until nothing is left and count the number of subtractions. Only then does an astonished expression show that, for the first time in their lives, they have begun to comprehend the meaning of division.

Fortunately, the opportunity to exercise these primitive aspects of arithmetical reasoning and solution of "word problems" arises repeatedly in the CIPS work and does so in contexts of rather concrete experience: density, solubility, combining proportions (how much oxygen combines with one gram of carbon, given the percentage composition of the compound), etc. We expand this context by a digression into the properties of circles because we eventually want to calculate the radius of the Earth by the method of Eratosthenes. (Most students would readily regurgitate the formula for the circumference of a circle, but we sneak around this by asking them to measure the circumferences and diameters of an array of cylindrical objects and make a running plot of circumference versus diameter. When they examine the "steepness" or "slope" of the graph in the manner they have examined other straight line graphs and recognize 3.14 as a <u>property</u> intrinsic to <u>all</u> circles, one frequently hears soto voce remarks such as "<u>that</u> is what they meant by pi ! ")

By the end of the first quarter, at least 75% of the students can tackle an arithmetical problem successfully, explain the line of reasoning clearly and intelligibly in their own words, and point to some other problem of their own invention in which the line of reasoning is identical. When we subsequently go on to velocity, acceleration, and the description of motion in the

Project Physics sequence, these abstractions no longer appear as almost insuperable obstacles. The students can focus their attention on the abstract concepts themselves and are not simultaneously overpowered by the arithmetical mystique of dividing displacement by the time interval in which the displacement occurred.

Another aspect of logical thought (and indeed comprehension of the very nature of science) resides in the ability to separate statements of fact and observation from inferential or explanatory statements about these facts. At one point in the CIPS work the students heat metallic copper in an open crucible, monitoring any changes in weight that occur. The copper is seen to turn black and powdery; the weight of the material increases. We have discovered that if we go around and ask the students what they have observed up to this point, an almost universal response is, "we observed oxygen combining with the copper."

The point of the sequence, of course, is that we observe an increase in weight on heating copper in contact with air. Having established the idea of conservation of mass, we infer that something from the air may have joined the copper to form a new substance. The "something from the air" is the beginning of a definition of the substance to which we will eventually give the <u>name</u> "oxygen."

This deep confusion among facts, observations, inferences, explanatory statements, and technical terms is prototypical. Experiences of the kind described in the copper experiment must be generated repeatedly in connection with other phenomena (chemical processes, motion, light, electricity) before the logical and intellectual point is firmly registered.

It is a depressing reflection on much of what our students have been "taught" that they come to us deeply imbued with the notion that knowledge resides in names. They talk about "energy", "molecules", "electrical charge" with great abandon but without any idea of what these words mean or what experiences give them sanction. They have no genuine conception of the distinction between "heat" and "temperature" or between "velocity" and "acceleration". They conceive of energy and electrical charge as material substances rather than as abstract concepts. They say with perfect innocence (as their teachers told them) that "objects fall <u>because</u> of gravity" and are astonished at being shown that we have no idea of what gravity "is", or how it "works", that the technical term simply conceals our ignorance, and that the real justification for the name lies in the profound recognition that the same effect, whatever it may be, holds the moon to the Earth and the Earth to the Sun.

A slogan of our course has become "the idea first and the name afterwards." In conversation during laboratory work, on check-outs at the ends of units, on tests and quizzes, we firmly insist that students be able to describe an idea in simple words of prior definition before we acknowledge that we understand the meaning of the technical term. This is a potent discipline, which the students at first find frustrating and subsequently begin to appreciate.

In addition to a design aimed at cultivating the aspects of learning, logical thought, conceptual understanding that we have emphasized above, the course has explicit general education objectives. We seek to have students see science as a product of human imagination, an enterprise of enormous power and profound limitations. An effort is made to show them that an understanding of science plays the same role in their growth as educated men and women as do an awareness of history and sensibility to literature.

On reaching the point in the CIPS work at which we begin to rationalize the accumulated facts and observations concerning the behavior of material substances by creating a model for matter on the microscopic scale, we generate discussion in which students pit continuous versus discrete models. Proponents of a continuum model are usually forced into the position of saying that different gases have identical expansion properties, or crystals form with particular angles and symmetries, because the substances "want" to behave that way. When we then describe the rejection of teleological or "occult" properties of inanimate matter by 17th century natural philosophers such as Galileo and Newton, this facet of modern science takes on more than purely verbal significance.

After building a tentative atomic-molecular model on the basis of observed physical phenomena and the chemical law of definite proportions, we follow Dalton's prediction of the law of multiple proportions and look for this regularity in the superficially unrevealing percentage compositions of different compounds formed by the same pair of elements. In Dalton's day the percentage compositions had been known for years, but no one ha^d noticed the regularity they had concealed. The point here, of course, is that "facts" frequently do <u>not</u> speak for themselves. In this case they were not even seen until looked for through the lenses of a theory, and their verifiaction became dramatic evidence in favor of the theory itself.

From the beginning of the course in September, while CIPS and Project Physics materials occupy most of the class time, students work more or less extracurricularly on what is essentially the content of the Elementary Science Study unit on Daytime Astronomy. As in the other work, they are guided by unit outlines which define observational tasks and ask questions: What is meant by "local noon" and "midnight"? How would you establish a north-south line on the pavement outside the laboratory? Does the sun rise and set at the same points on the horizon from day to day? Do the stars change position relative to each other or relative to the local horizon during the course of the night? What are the facts of observation about the phases of the moon? What evidence do we have to support the view that the distance of the Sun must be many, many times the size of the Earth? (From observations of the noontime shadow angle of a vertical stick at the equinox, the students eventually calculate the radius of the Earth in the manner of the famous calculation of Eratosthenes.)

From time to time, accumulating information, observations, and inferences are synthesized and extended in class discussion. As the students start arguing about heliocentric versus geocentric models of the solar universe, they begin to see that the simple observations we have been making cannot validate one model as "correct." They see that they have accepted the proposition that the Earth revolves around the Sun only by deference to authority without any understanding of why the proposition is accepted. The question of validation of the model is not closed at this point; the problem is left open for further study.

After subsequent study of motion, force, and the Newtonian Synthesis in the Project Physics materials, we see how the 18th century accepted the heliocentric model because of the quantitative successes of the theory, because of the grand perception that the same laws, comprehensible to the human intellect, describe order in both celestial and terrestrial phenomena. It is seen that this unified view of the universe, with its concomitant deep alteration of man's view of his position in it, was accepted on the basis of the compelling success of a scientific theory long before direct confirmation ~~came~~ emerged through the observation of stellar parallax.

Toward the end of the course we have students take turns signing out a super-8 movie camera for a day or two. They are to come back with 30 seconds worth of film of some phenomenon that they see to be connected with ideas and concepts we have studied. When a roll is full, the film is processed and shown in class, with each student presenting his own footage and explaining the physics that he saw. The richness of many of the films is surprising and rewarding, and everyone has a good time. The pay-off comes a week or so later, however, when a student comes to class with a light in his eyes and says, "I wish I had that camera yesterday; I saw something that would have been.........." One need hear no more.

In summary, we feel that we have evolved a viable program based on existing curricular materials; meeting the students at their present level of intellectual development; presenting a model of teaching and learning consistent with that implicit in the new elementary materials; allowing students time to struggle, observe, make mistakes, retrace their steps, thus achieving both long delayed intellectual develpment and insight into scientific knowledge; and conveying, through careful examination of how we know and why we believe, some sense of the nature, successes, and limitations of scientific thought, together with a sense of how this thought came to have so deep an impact on our view of ourselves and our place in the universe.

References:

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[2] The Project Physics Course. Holt, Rinehart, and Winston. New York. 1970.

[3] McKinnon, J.W. and Renner, J.W. "Are Colleges Concerned with Intellectual Development?" American Journal of Physics 39: 1047-52; 1971.